

# ROTATION OF HOT HORIZONTAL BRANCH STARS IN THE GLOBULAR CLUSTERS NGC 1904, NGC 2808, NGC 6093 AND NGC 7078<sup>1</sup>

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## ABSTRACT

We present high resolution UVES+VLT spectroscopic observations of 56 stars in the extended horizontal branch (EHB) of the Galactic globular clusters NGC 1904, NGC 2808, NGC 6093, and NGC 7078. Our data reveal for the first time the presence in NGC 1904 of a sizable population of fast ( $v \sin i \geq 20$  km/s) horizontal branch (HB) rotators, confined to the cool end of the EHB, similar to that found in M13. We also confirm the fast rotators already observed in NGC 7078. The cooler stars ( $T_{\text{eff}} < 11,500$  K) in these three clusters show a range of rotation rates, with a group of stars rotating at  $\sim 15$  km/s or less, and a fast rotating group at  $\sim 30$  km/s. Apparently, the fast rotators are relatively more abundant in NGC 1904 and M13, than in NGC 7078. No fast rotators have been identified in NGC 2808 and NGC 6093. All the stars hotter than  $T_{\text{eff}} \sim 11,500$  K have projected rotational velocities  $v \sin i < 12$  km/s, but less than 20% have  $v \sin i < 2$  km/s. The connection between photometric gaps in the HB and the change in the projected rotational velocities is not confirmed by the new data. However, our data are consistent with a relation between this discontinuity and the HB jump. We discuss a number of possibilities for the origin of the stellar rotation distribution along the HB. We conclude that none of them can yet provide a satisfactory explanation of the observations.

*Subject headings:* globular clusters: general — stars: horizontal-branch — stars: rotation

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## 1. Introduction

Several unresolved issues in advanced stages of stellar evolution revolve around the nature of stars in the Horizontal Branch (HB). In particular, an increasing number of Globular Clusters (GCs) have been found to show HB blue tails (Ferraro et al. 1998, F98, Piotto et al. 1999, P99), which sometimes extend all the way to the He-burning main sequence (extended HB stars, EHB), indicating that some of the stars must have lost (almost) all of their envelope during the red giant branch (RGB) phase. We now know that these extremely hot HB stars can be found in clusters of any metallicity, including in metal rich GCs (Rich et al. 1997). Yet, the origin of EHBs is still a puzzle. Stellar evolution models indicate that EHB stars are He-core, H-shell burning stars, which have lost almost their whole envelope during the RGB ascent (Greggio & Renzini 1990; D’Cruz et al. 1996), with a residual envelope mass  $\leq 0.02M_{\odot}$ . The problem is that we do not know *why* EHB stars have lost so much mass. Understanding the origin of EHB stars in GCs has a more general relevance in astrophysics, as these very hot stars are now considered the prime contributors to the ultraviolet emission in elliptical galaxies (Greggio & Renzini 1990; Brown et al. 2000).

One more puzzling peculiarity is shared by all the EHBs discovered so far: one or more gaps are found in the stellar distribution along the EHBs, with sections of the HB that are clearly underpopulated (Sosin et al. 1997, F98, P99), as if mass loss prior to the HB phase was somewhat *quantized*. Moreover, there is evidence that the GC density favours the appearance of EHBs (Fusi Pecci et al. 1993), hinting that stellar interactions may favour in some way the extreme mass loss that is required (Sosin et al. 1997). Other candidate scenarios include mixing during either the RGB phase or as a result of a core helium flash in hot stars (Sweigart 1997; Brown et al. 2001), and stellar rotation (Peterson et al. 1995, P95). In this paper we will focus on stellar rotation rate, investigating whether it is somehow related to the EHB properties.

Recently, Behr et al. (2000a, B00a) have suggested the existence of a discontinuity in stellar rotation velocity across one of the gaps (at  $T_{\text{eff}} \simeq 11.000$  K) in the EHB of M13. Bluewards of the gap, all the stars show modest rotations ( $v \sin i < 10$  km s $^{-1}$ ), while to the red side of the gap several rapidly rotating stars are found (with  $v \sin i$  up to 40 km s $^{-1}$ , see also P95). A similar discontinuity was also found for M15 (Behr et al. 2000b, B00b). On the other hand, the quick rotation of the M13 HB stars is even more suggestive when compared with the slower  $v \sin i < 20$  km s $^{-1}$  found in clusters without an EHB, such as M3 and NGC 288 (P95), suggesting a possible connection between rotation and EHBs.

More observations of GCs with different HB morphologies are needed to understand the role played by rotation on EHB stars. For this reason, we started an observing campaign with the UVES high resolution spectrograph at VLT. In this paper, we present the results on

the rotation of 56 HB stars in 4 GCs: NGC 1904 (M79), NGC 2808, NGC 6093 (M80), and NGC 7078 (M15). The new observation double the number of EHB stars for which projected rotational velocities have been measured. The observations of much larger samples will soon become possible with the forthcoming multifiber facilities, such as FLAMES at the VLT.

## 2. Observations

Our spectra were collected using the VLT-UVES spectrograph on Jul 30 - Aug 2 2000, and Jan 19-23 2001. A 1.0 " slit width yielded a nominal resolution of  $R = 40,000$ . The UVES blue arm, with a spectral coverage in the 373 - 499 nm range (where many tens of metallic lines were expected, and, indeed, identified), has been used. S/N ratios were always  $\geq 10$  per resolution element.

As the measurement of  $v \sin i$  by line broadening is inherently statistical, we have observed more than 10 stars per cluster. Twenty stars in M79, 11 stars in M15 and 6 stars in M80 were selected from the HST-WFPC2 images and photometry of the HST-snapshot program by Piotto et al. (2002, cf. <http://menhir.pd.astro.it>). Five additional stars of M80 were selected from the Johnson *VI* photometry by Rosenberg et al. (2000). Finally, the 11 NGC 2808 stars were from the CMD in Bedin et al. (2000). The target stars have a temperature in the range  $8,000 \leq T_{\text{eff}} \leq 28,000\text{K}$ , and are equally distributed on the two sides of the gap at  $T_{\text{eff}} \approx 11,000\text{K}$  present in the EHB of the 4 GCs. Figures 1 and 2 (right panels) show the position of the target stars (full and open circles) on the HB blue tails. In general, all the program stars lie in the GC's low crowding outskirts. The CCD imaging confirmed the absence of faint companions. During each observing night, we have also collected high S/N spectra of a set of field rotational velocity standards (Peterson et al. 1983), with spectral types close to that of our program blue HB stars: HD74721 ( $3 \pm 3$  km/s), HD130095 ( $3 \pm 3$  km/s), HD117880 ( $12 \pm 3$  km/s), HD19445 ( $13 \pm 3$  km/s), and HD109995 ( $27 \pm 3$  km/s).

## 3. Data Analysis and Results

We used the standard IRAF procedures to reduce the spectra. For the determination of the projected rotational velocities we used the cross-correlation technique described by Tonry and Davis (1979). This method is well suitable to measure rotational broadening in low signal-to-noise spectra (Dubath et al. 1990). The analysis procedure computes (in the Fourier domain) the correlation function of the object spectrum versus that of a template, fits a gaussian to the highest peak, and finds the radial velocity and the line broadening

from the peak’s central position ( $\delta$ ) and width ( $\mu$ ). If the Gaussian instrumental width is  $\tau^2$ , then a template to template correlation gives a width  $2\tau^2 = \sigma_o$ , while a template to object correlation gives a width  $\mu^2 = \sigma_o^2 + \sigma^2$ , where  $\sigma$  takes account for the rotational broadening difference between the template and the standard. Finally, the projected rotational velocity  $v \sin i$  can be expressed by (Melo et al. 2001):  $v \sin i = A\sqrt{\mu^2 - 2\tau^2} = A\sigma$ , where  $A$  is a constant coupling the differential broadening of the cross-correlation peak,  $\sigma$ , to the  $v \sin i$  of the stars. The constant  $A$  in the previous equation was found for each rotating standard star by fitting the relation  $(v \sin i)^2$  versus  $\mu^2$  by a straight line for which the square root of the slope gives  $A$ . The mean value  $\langle A \rangle = 1.8 \pm 0.7$  km/s was adopted. Each target spectrum was divided into regions (avoiding hydrogen lines) of about 40 angstroms, and cross-correlated with the templates, using the task *fxcor* within IRAF. A value of  $v \sin i$  was calculated for each cross-correlation function, rejecting those correlations for which the peak’s central position does not agree with the correct stellar radial velocity relative to the template. In this way, we avoid errors due to line mismatch or to the lack of spectral features, specially for the hottest stars and the reddest sections of the spectra. Finally, for each program star, we calculated the weighted mean (typically, from 15 orders) of the  $v \sin i$  values and the corresponding root mean squares. We used as weight the height of the cross-correlation peak. Different templates give consistent  $v \sin i$ . Possible systematic errors caused by the dependence of  $\sigma_o$  on other broadening mechanisms, as microturbulence, are negligible compared to the calculated statistical error ( $\sim 3$ -4 km/s). More details on the data reduction, and a table with positions and velocities of the single stars will be published in a forthcoming paper.

The projected rotation results for the 56 stars in the 4 GCs observed in this study, and for M13 (from B00a and P95), are shown in Figs. 1 and 2. For M15, we plot both our and B00b data. The  $v \sin i$  for two M15 stars we have in common with B00b are in agreement within the errors ( $5 \pm 2$  vs.  $5.07 \pm 0.24$  and  $13 \pm 3$  vs.  $14.88 \pm 0.69$ ), showing a consistency between the two sets of observations, and between the two independent methods adopted for the rotational velocity measurement.

An estimate of the  $T_{\text{eff}}$  for each star has been obtained by comparing the Cassisi et al. (1999) models with observed CMDs. In particular, we used the *uy* Strömgren photometry for M79 (Grundahl et al. 1999, G99); the Johnson *UB* for NGC 2808 (Bedin et al. (2000), and the HST F439W and F555W for M80 and M15 (Piotto et al. 2002). Hence, there might be some offset in the temperature scale from GC to GC, in view of the different photometric systems (the temperatures for the M13, M80 and M15 stars being the most uncertain ones), but for the purpose of this paper only the relative position with respect to the HB gaps is relevant. The gaps on each GC HB are marked with arrows at the positions suggested by Hill et al. (1996) for M79 ( $T_{\text{eff}} = 9,900\text{K}$ ), and F98 and P99 for the other GCs, i.e  $T_{\text{eff}} = 11,000\text{K}$

for M80;  $T_{\text{eff}} = 9,000\text{K}$  for M15;  $T_{\text{eff}} = 11,000\text{K}$  for M13. For NGC 2808 we adopted  $T_{\text{eff}} = 15,900\text{K}$  for the gap position, following Bedin et al. (2000). A second vertical arrow marks the position of the luminosity “jump”, taken from G99. The “jump” is a discontinuity in the Strömgren ( $u$ ,  $u-y$ ) locus for which stars in the range  $11,500 \leq T_{\text{eff}} \leq 20,000$  K deviate systematically from (in the sense of appearing brighter and/or hotter than) canonical zero-age HB models (cf. Fig. 2). The jump seems to be an ubiquitous feature, intrinsic to all HB stars hotter than 11,500 K (G99). The jump is also visible in the  $UB$  photometry of Fig. 1.

A first result from this investigation is that in all GCs *all the stars hotter than  $T_{\text{eff}} \sim 11,500$  K have  $v \sin i \leq 12$  km/s*. This result is based on 116 stars in 5 GCs (including the 31 stars in M13 and M15 from B00a and B00b, and the 29 stars in M13 from P95). The measurements obviously provide  $v \sin i$ , but for an isotropic distribution in rotational axis large  $\sin i$  are more likely than small ones, being for example the probability that  $\sin i \leq 0.25$  about 3%. Therefore, the bulk of these stars must be intrinsically slow rotators. Still, it must be stressed that very few stars (less than 20%) have projected rotational velocities below 2km/s (the rotational velocity of the Sun). Even the “slow rotators” have, on average,  $v \sin i \sim 7$  km/s. Only in NGC 2808, 50% of the stars have projected rotational velocities compatible with a zero value. The small number of stars do not allow us to conclude whether the HB stars of this GC are really peculiar or whether this is just a statistical fluctuation.

In addition, our data reveal for the first time the presence in NGC 1904 of a sizable population of fast HB rotators ( $v \sin i \geq 20$  km/s) confined to the cool end of the blue HB. We also confirm the fast rotators already observed by B00b in M15 (M15). Among the cooler stars ( $T_{\text{eff}} < 11,500$  K) in these three GCs there is a range of rotation rates, with a group of stars rotating at  $\sim 15$  km/s or less, and a fast rotating group at  $\sim 30$  km/s. Apparently, the fast rotators are relatively more abundant in M79 and M13, than in M15, where only 3 stars out of 22 rotate faster than 15 km/s. In M79 and M13, at least half of our stars cooler than 11,500K are fast rotators. This implies *a different intrinsic distribution in the rotation rates of the EHB stars in these 3 GCs*. Neither the  $v \sin i$  distribution in M13 and M79 nor that in M15 are as we could expect from a constant rotation rate and a random orientation of the axis.

Neither NGC 2808 nor M80 show any fast rotator in our sample. This may well result from too few HB stars cooler than 11,500K being included in our sample. However, there are quite many stars that are cooler than the gap, hence this result does not confirm the B00a suggestion that the abrupt change in the rotational velocity distribution was coincident with the presence of the EHB gap. All GCs in the present study have an EHB, and in all of them there is a HB gap. We were careful in having in all cases approximately half of the stars on either side of the gap, but Fig. 2 clearly indicates that the presence of fast rotators *is not*

related to the presence of the gap. Indeed, both in NGC 2808 and M80 there are 8 stars on the cool side of the gap, and none of them has a rotational velocity exceeding 10 km/s. The likelihood that the small  $v \sin i$  values on the cool side of the gap in NGC 2808 and M80 are due to casual almost polar orientation is very small, and therefore these stars are most likely intrinsic slow rotators. Notice also that one star in M15 with  $v \sin i = 23 \pm 3$  km/s is located significantly bluewards of the gap.

We conclude that *the EHB gaps are not related to the abrupt change in the rotational velocity distribution of the HB stars*. On the other hand, Fig. 2 indicates that all the fast rotators in M15 are cooler than  $T_{\text{eff}} \sim 11,500\text{K}$ , i.e. cooler than the location of the G99 jump, rather suggesting a link between the presence of the jump and the absence of fast rotators among stars hotter than this temperature.

#### 4. Discussion.

Along with similar previous studies, the present investigation demonstrates that HB stars in GCs rotate, and do so much faster than the Sun, in spite of braking mechanisms having been at work for  $\sim$  one Hubble time. This suggests that either the stars are able to preserve part of their angular momentum all the way through very advanced evolutionary stages, or that they may re-acquire angular momentum, for example, as a result of tidal interactions in the high density environment offered by GCs.

It is quite possible that the envelope of stars is completely deprived of its angular momentum during the RGB phase, when at least half of this envelope is lost in a wind. Suffice indeed even a small magnetic field for efficiently transferring angular momentum from the whole convective envelope - which tends to rotate solid body - to the wind. However, the very small, degenerate core may still retain angular momentum, and on this hypothesis Mengel & Gross (1976) constructed evolutionary models with core rotation. In these models rotation has the effect of delaying the helium flash until the star reaches a slightly higher luminosity on the RGB. However small the effect, it would be sufficient to allow more mass to be lost by more rapidly rotating stars, offering an explanation for the origin of the mass dispersion along HB stars (Renzini 1977). This scenario is in apparent conflict with the observations of stellar rotation among EHB stars reported above, because one would expect the fast rotators to lose more mass than slow rotators, hence landing at higher temperatures on the HB. The opposite is instead observed: the hottest EHB stars are all slow rotators, while the fast rotators are found only below  $\sim 11,500\text{K}$ .

Another embarrassment comes from the mere fast rotation itself: what rotates is the

stellar envelope, which should have lost all its angular momentum prior to the star beginning its HB phase. Sills & Pinsonneault (2000) proposed models for the angular momentum evolution in which no magnetic braking takes place, and stars retain some envelope rotation and a rapidly rotating core during the RGB phase. Once on the HB, angular momentum redistribution from the core to the envelope would spin up the envelope. However, in spite of being based on assumptions that favor angular momentum retention, these models fail to predict the high rotation observed below 11,500K, coupled with the low rotation observed at higher temperatures. So the puzzle remains.

Sills & Pinsonneault (2000) argue that diffusion of heavy elements in the hottest stars may prevent angular momentum transfer from the core, due to the build up of a gradient in mean molecular weight ( $\mu$ ). However, core and envelope have quite different  $\mu$  anyway, hence diffusion does not look a viable alternative. Maybe core-envelope angular momentum transfer takes place after all, but in stars hotter than  $\sim 11,500\text{K}$  angular momentum is continuously removed via the radiatively accelerated wind typical of hot stars. Indeed, the mass loss rate may increase by a large factor between  $\sim 10,000$  and  $20,000\text{K}$  (Vink et al. 2000), and may become very small below  $\sim 10,000\text{K}$ , i.e., at the temperatures of most fast HB rotators. While also this remains a speculative solution to the puzzle of the hot slow rotators, still the cooler fast rotators seem to require a quite contrived angular momentum history. Angular momentum extraction from the core should be quite inefficient during the RGB (in order to maintain an angular momentum reservoir), and quite efficient during the HB (in order to promptly spin up the envelope). We also note that there is no apparent correlation between rotational velocity and luminosity *distance* from the ZAHB (cf. Fig. 1 and 2, right panels), as would result if the timescale of angular momentum diffusion were comparable to the HB lifetime.

As already mentioned, besides all these complications the mere existence of fast rotators is not so obvious, given the ample opportunities to lose angular momentum along with mass during the RGB phase. Soker (1998) has proposed that fast HB rotators could have spun up by swallowing close planetary companions during the RGB phase. However, no planetary companions have been found in a very intense search for them in the GC 47 Tuc (Gilliland et al. 2000), which seems to exclude this possibility. Quite more attractive is the hypothesis of an envelope spin up as a result of close tidal encounters of RGB stars with main sequence dwarfs. This scenario is circumstantially supported by the noted correlation of the presence of an extended EHB with the cluster density (Fusi Pecci et al. 1993), with very extended EHBs being found almost exclusively in the densest GCs. So, tidal encounters may account for both enhanced mass loss (e.g. stripping) responsible for the blue extension of the HB, and for the enhanced rotational velocities of some HB stars. But for the hot slow rotators another effect must be invoked.

Mass and angular momentum loss during the EHB phase itself has been mentioned above, and the noted coincidence of the drop in rotation with the luminosity jump may provide support to this hypothesis. B00a has noted the coincidence between the discontinuity in the rotational velocity and the appearance of composition anomalies, most likely due to diffusion (see also Glaspey et al. (1989)). Following Greenstein et al. (1967), gravitational settling of helium and radiative levitation of metals can occur in the stable, non-convective atmospheres of the hot, high gravity HB stars. This possibility has been observationally confirmed by Behr et al. (1999) and B00b for M13 and M15, and the jump in the HB luminosity may be caused by the onset of metal levitation (see also Moehler et al. 2000). The fact that the change in the velocity distribution can be associated to the jump (instead of to the gap) makes the entire scenario observationally consistent, especially when also noting that the enhanced surface abundance of metals will further boost mass (and angular momentum) loss via radiation pressure on such elements.

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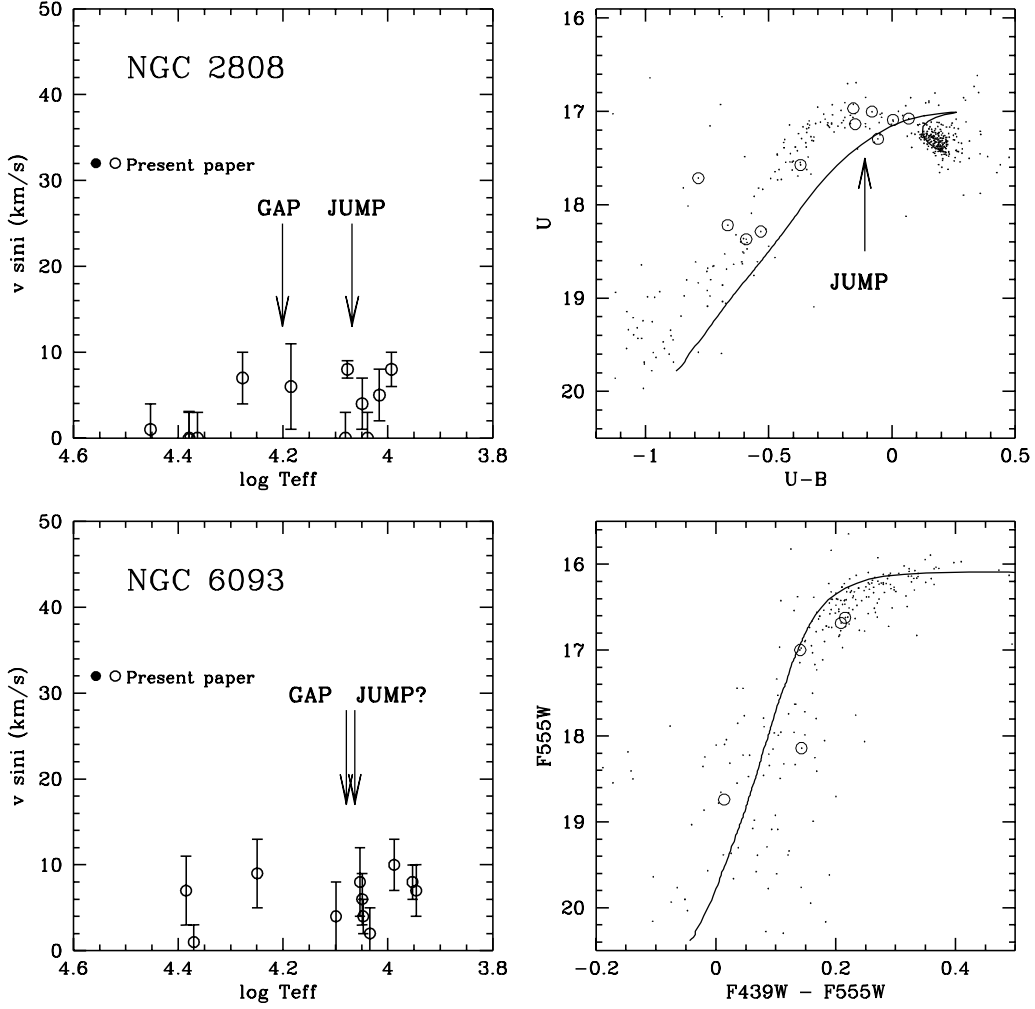


Fig. 1.— Left panel: Projected rotational velocities as a function of the temperature for our targets in NGC 2808 and M80 (open circles). The vertical arrows indicate the positions of the “gaps” (from F98 and P99) and of the “jump” (from G99). The position for the jump in M80 has not been confirmed by observations, yet. We just put the arrow in correspondence of  $T_{\text{eff}} = 11,500\text{K}$  where all the HBs of G99 GCs show this feature. Right panel: location of the target stars in the CMD. The full line represent the best fitting ZAHB from Cassisi et al. (1999).

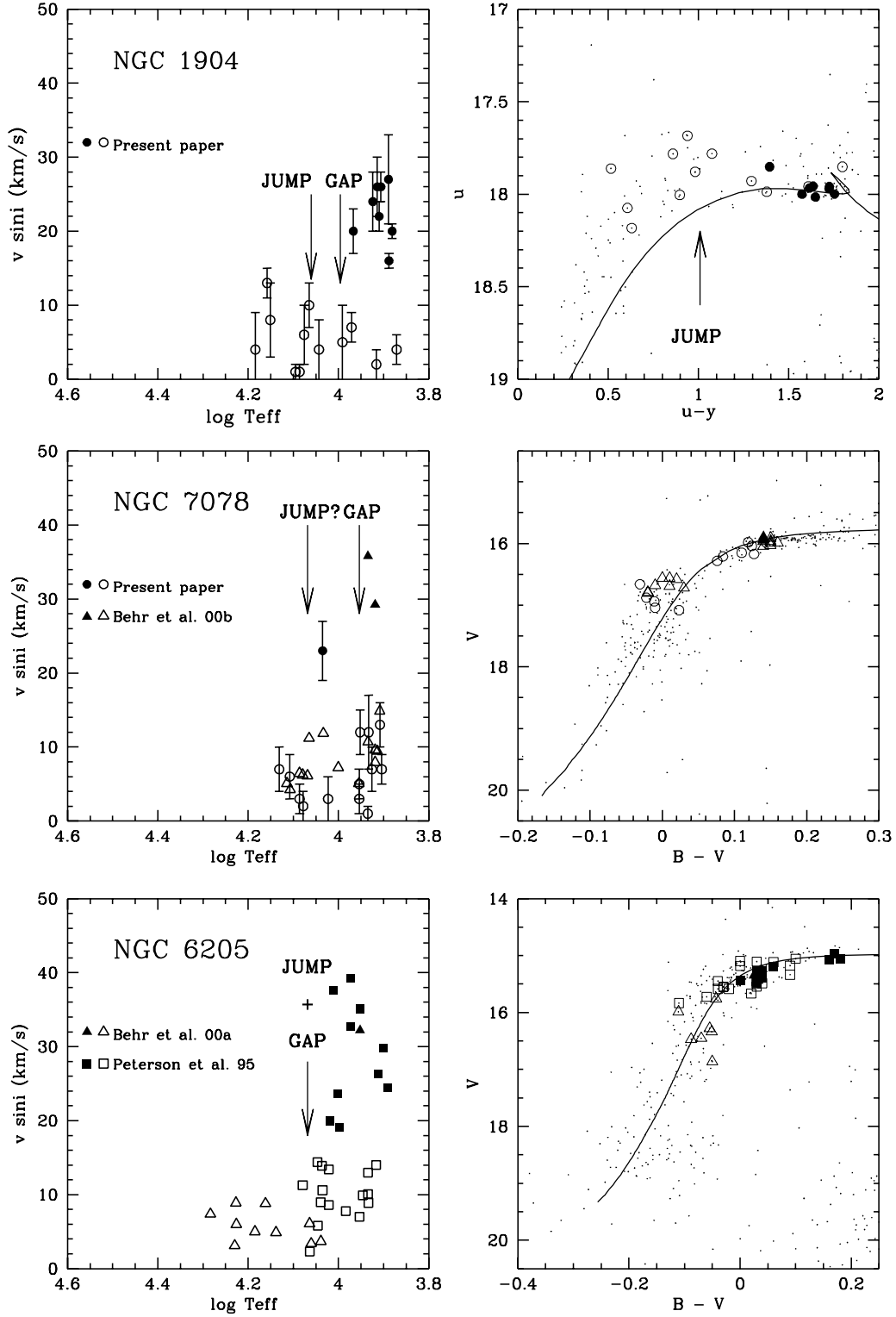


Fig. 2.— As in Fig. 1 for M79, M15, and M13. Full symbols show  $v \sin i \geq 15$  km/s stars.